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Nano-selective area growth of InGaAs/InP using CBr₄ in-situ etching

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Abstract: We are investigating the conditions for nano-patterned selective area epitaxial growth using e-beam lithography on HSQ resist and in-situ etching in the MOVPE reactor.

OCIS codes: (160.4236) Nanomaterials; (250.5590) Quantum-well, -wire and -dot devices; (220.4241) Nanostructure fabrication

1. Introduction

Accurate positioning of high-quality nano-scale active material is essential for the realization of future high-efficiency active nanophotonic devices. QWs, QWires or QDs as gain material allow precise tuning of the wavelength but for e.g. photonic crystal devices the position is also important.

We present selective area MOVPE growth of InGaAsP/InP compounds in the 1.55 μm wavelength region for telecommunication applications. In-situ etching is used before growth to provide clean defect-free surfaces. The method of fabrication allows us to obtain smooth material on the top surface suitable for creating high-Q cavities. The goal of the work is the demonstration of photonic crystal lasers and switches based on QDs and QWs. For conventional all-active, i.e. with quantum wells or dots all-over the wafer, photonic crystal structures optical pumping exhibit a poor efficiency as the pumping area is determined by the pump beam spot size and determines the volume that is bigger than cavity mode volume. This creates a heating problem that can be solved using InGaAs active area in selected places and a pump which is only absorbed in this region so the total absorption is reduced. Also, surrounding the material with a high thermal conductivity material like InP reduces the thermal resistance [1]. The ability to place gain material in well defined places based on the calculation of the optical field of photonic crystal can increase efficiency and limiting losses. Further improvement may be achieved using slow-light waveguides.

2. Fabrication

Investigated structures were fabricated on (001) InP substrates by e-beam writing (JEOL-JBX9300FS) and low pressure MOVPE reactor at 60 Torr. A hydrogen silsesquioxane (HSQ) mask protects the epitaxial regions from further etching and growth making this area passive. HSQ is a negative tone resist that is converted to silicon oxide after e-beam exposure making a MOVPE compatible mask directly. This avoids the deposition and etching of an additional glass layer and removing e-beam resist before growth [2]. The small molecular size and high etching resistance is suitable for getting small feature sizes and perform in-situ etching [3].

Patterns for quantum wells, quantum wires and arrays of QDs are drawn by e-beam lithography (fig. 1). To achieve the desired quantum confinement effect for the QDs, the nano-openings have to be done with 10 nm accuracy. In figure 1 (right) is shown the pattern for an array of QDs with 15 nm size squared - shape and 40 nm line width.

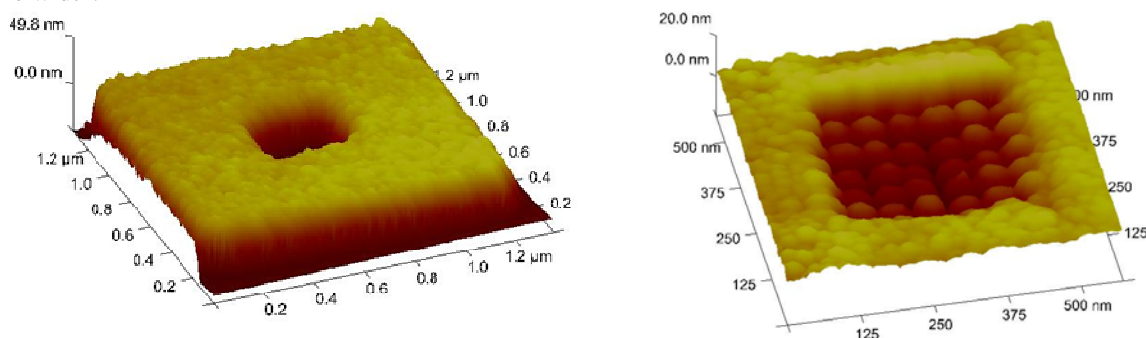


Fig. 1 AFM picture of HSQ pattern after e-beam lithography for QWs (left) and QDs (right)

To bury the InGaAs/InP material in an InP matrix in-situ etching by CBr₄ was done [4]. Concentrated sulphuric acid is used to remove the native oxide before loading the wafer in the MOVPE chamber. 15 min thermal de-oxidation at 650°C under PH₃ was done before CBr₄ etching and epitaxial growth was done. The reason for doing the final etching in the MOVPE reactor is to prevent the surface from re-oxidation especially in the corners of the groove where thermal de-oxidation may be difficult. The crucial point in the growth process is to achieve clean defect free interfaces to avoid the non-radiative recombination processes.

The used MOVPE machine does not have any tools for monitoring a wafer during etching and growth process in-situ. Two cycles of 5 nm InGaAs/10 nm InP layers were grown to determine the groove profile after etching and the growth evolution. Selective wet etching of the InGaAs layer was done to get good contrast in scanning electron microscopy (SEM) images. Selective grown structures usually is bounding by the slowly growing crystallographic planes. The practical importance is the control of the shape and the optical quality of such structures. Changes in the shape of the etched groove have been observed for different crystallographic directions (figure 2).

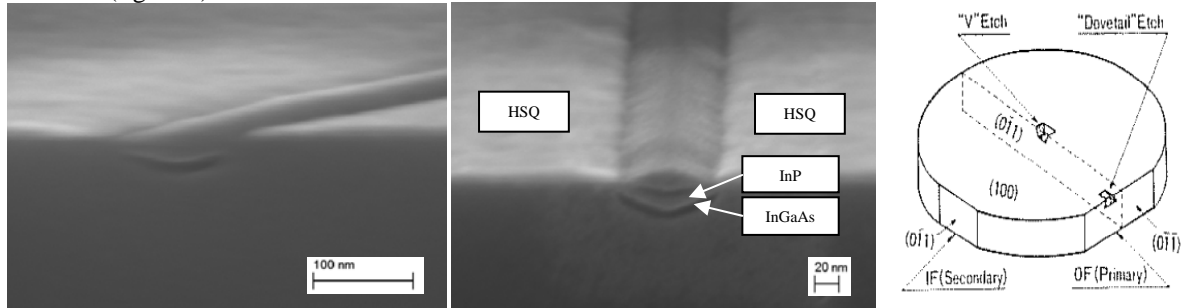


Fig. 2 SEM images of etched of InP (a) directed along $[111]$ (b) Directed along $[0-1-1]$ and drawing of crystallographic orientation in a InP wafer. Dark layers are InGaAs, the rest is InP

Surface kinetic limitation inhibits the deposition on the HSQ mask. All atoms move from the mask to the uncovered surface. The effect of growth enhancement is observed near the mask leading to nonuniform growth due to the source gas concentration differences between the masked and the growing surface.

Changes in the distribution of active material can be observed for different width of the opening [5]. The groove after etching is a trapeze in $[0-11]$ direction. The angle of the sidewalls is constant for different opening widths leading to a transition from a trapeze to a triangular groove. For 250 nm opening the InGaAs follows the shape of a groove, but for 100 nm opening the active material is mostly buried in the InP matrix (figure 3). The first grown layer (InP) starts filling out the corners that are the energetically preferable place for deposition of material. The behaviour of the InGaAs is different as it grows on the top which creates the non-uniform shaped seen.

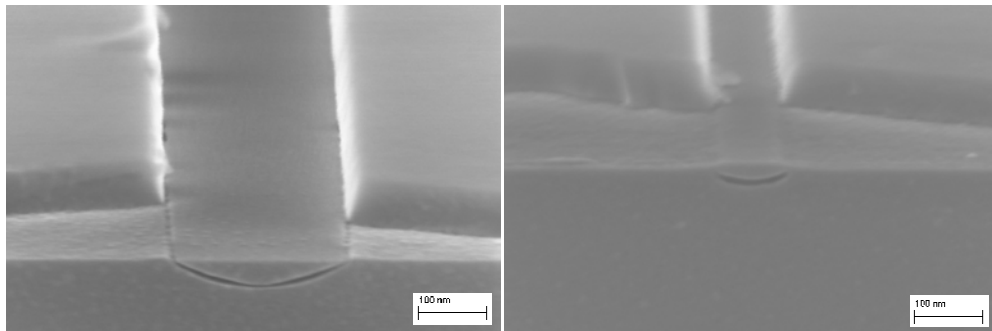


Fig. 3 SEM images of a buried InGaAs single QW of 250 nm (left) and 100 nm (right) width with HSQ mask on $(0-11)$ InP plane

3. Investigation

A micro-photoluminescence set-up (μ PL) is used to investigate optical quality of the SAG material. Three effects can be considered to influence the wavelength shift of SAG material compared to the easily measured QW far away from the mask. The increased thickness from the growth enhancement provides a red shift. Two HSQ line widths 500nm and 3 μ m was used for the study. However, because the diffusion length of In atoms is higher than that of Ga atoms, the Ga concentration is higher in the selected grown heterostructure which leads to blue shift of the wavelength. The third effect relates to quantum structures. Different energy quantum levels are different for different types of quantum structures. The energy levels in the wires are higher than in the QWs and this provides a further blue shift.

We investigated the needed thickness of the bottom InP layer through PL spectral measurements of the active material in the large area (fig. 4). Using a 5 nm InP layer below the InGaAs is quite good and suitable for device fabrication.

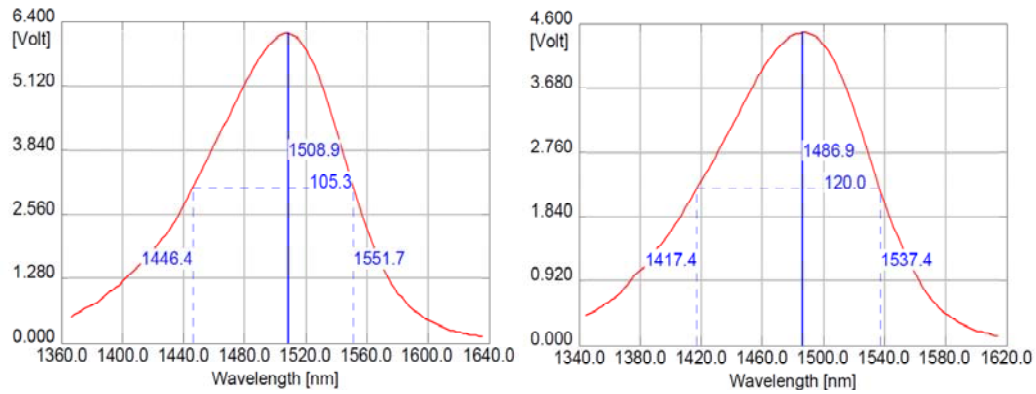


Fig. 4 Photoluminescence spectra of single QW with 50 nm (left) and 5 nm (right) InP layer

Detailed investigation of the atomic ordering in the semiconductor materials is necessary for understanding their properties. Needle shape specimens are shown in figure 5 for use in transmission electron microscopy (TEM) and atomic probe tomography (APT). The samples were prepared to investigate the three dimensional structural crystalline quality of the grown materials. The active material is placed at the end of the finger. Using wet etching and critical point dryer the specimens were membranized. We made an array of the blocks, cleaved them and the specimens are hanging in the air based to the substrate. Measurements are currently in progress.

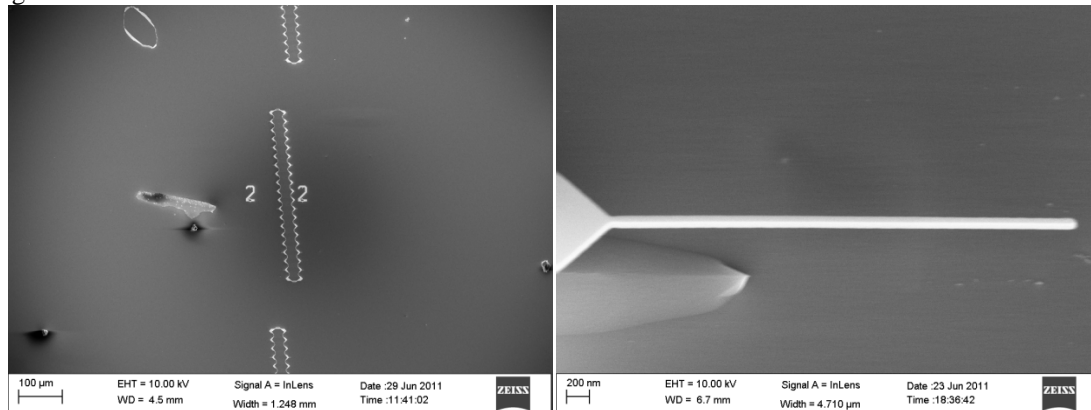


Fig. 5 SEM images of an array of the needle-shaped specimens

4. Conclusion

We have investigated the different crystallographic planes and shapes of buried QWs. We are keeping work on investigation of optical and crystalline properties of material. Smooth material on the top surface was achieved. The material seems to be promising for fabrication of optical devices of high quality.

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